

A Biologically Inspired Controller for Hexapod Walking: Simple Solutions by Exploiting Physical Properties

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Abstract. The locomotor system of slowly walking insects is well suited for coping with highly irregular terrain and therefore might represent a paragon for an artificial six-legged walking machine. Our investigations of the stick insect *Carausius morosus* indicate that these animals gain their adaptivity and flexibility mainly from the extremely decentralized organization of the control system that generates the leg movements. Neither the movement of a single leg nor the coordination of all six legs (*i.e.*, the gait) appears to be centrally pre-programmed. Thus, instead of using a single, central controller with global knowledge, each leg appears to possess its own controller with only procedural knowledge for the generation of the leg's movement. This is possible because exploiting the physical properties avoids the need for complete information on the geometry of the system that would be a prerequisite for explicitly solving the problems. Hence, production of the gait is an emergent property of the whole system, in which each of the six single-leg controllers obeys a few simple and local rules in processing state-dependent information about its neighbors.

Introduction

The advantages of legged locomotion in contrast to wheel-driven locomotion are particularly obvious in rough terrain. A disadvantage, however, is that legs can provide only discontinuous support of the body. At a certain point within its posterior working range, each leg has to be lifted off the ground and swung forward to regain ground contact for the next step. Hence during each step cycle each leg has to go through two mutually exclusive phases: the stance, in which the leg supports the body and can exert propulsion forces; and the swing, in which the leg cannot contribute to the movement of the body.

The control system that generates the leg movements of an animal faces several problems. During the stance, the trajectories of all leg endpoints have to be coordinated in such a way that each leg with ground contact contributes efficiently to propel the central body in the desired direction and with the desired velocity. Thus, in a six-legged animal with 3 joints per leg (Fig. 1a), as many as 18 joints have to be controlled. (For simplicity, the tarsus is considered as a passive foothold only, and the tip of the tibia is considered as the leg endpoint throughout this paper.) Four factors further complicate this control task: (1) the number and combinations of legs in stance vary continuously, (2) during curve walking, the legs move at different speeds, (3) on compliant substrates the movement of a leg may vary unpredictably, and (4) the geometry of the system may vary due to nonrigid suspension of the joints or due to injuries of leg segments. For the swing movement, it appears to be easier to solve the problems because no mechanical couplings *via* the substrate have to be considered. However, for the stability of an animal, the timing of the switch from

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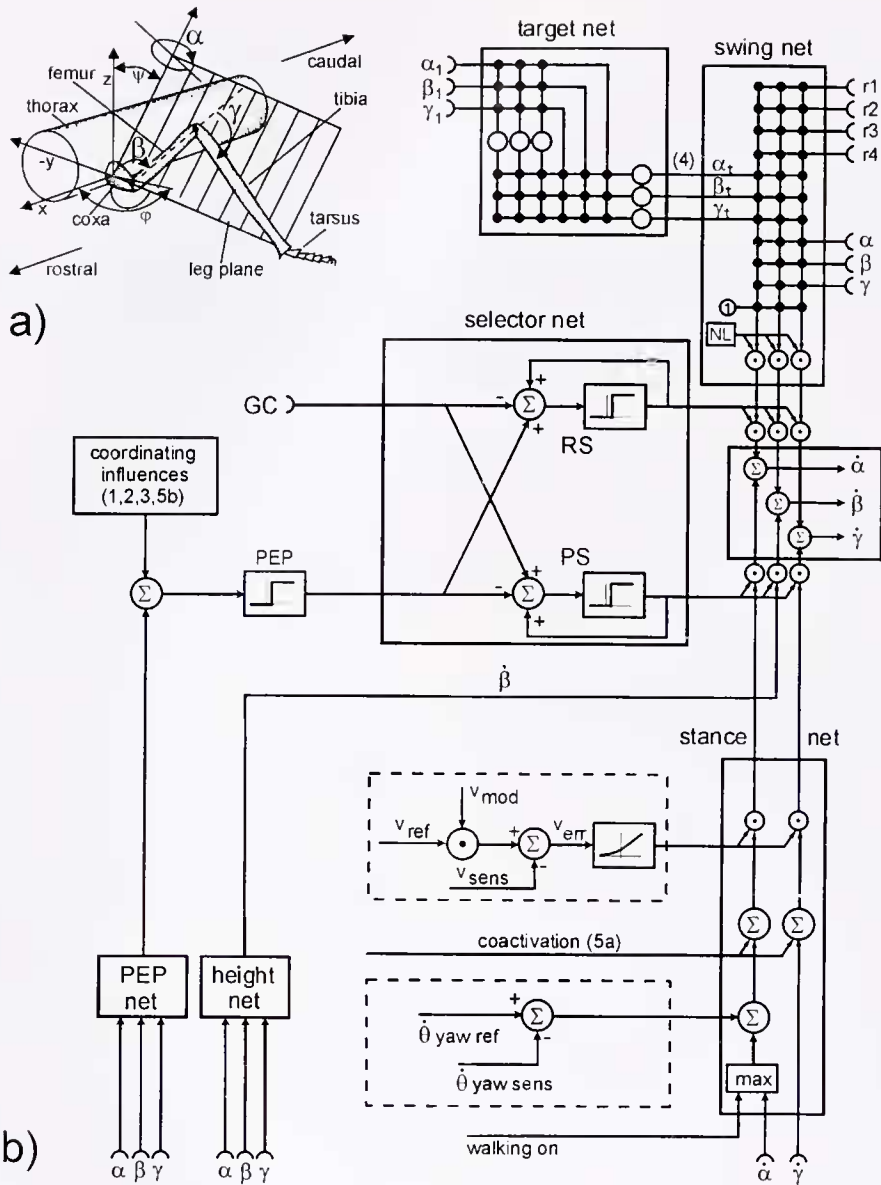


Figure 1. Summary of leg geometry and the single leg control network. (a) Schematic drawing of a stick insect leg showing the arrangement of the joints and their axes of rotation. (b) The leg controller consists of three parts: the swing net, which controls the leg movement during swing; the stance net, which controls the stance movement; and the selector net, which determines whether the swing or the stance net can control the motor output, *i.e.*, the velocity of the three joints α , β , and γ . The selector net contains four units: the PEP unit, which signals posterior extreme positions; the GC unit, which signals ground contact; the RS unit, which controls the return stroke (swing movement); and the PS unit, which controls the power stroke (stance movement). The target net transforms information on the configuration of the anterior target leg, given by the angles α_1 , β_1 , γ_1 , into angular values for the next caudal leg (α_t , β_t , γ_t), which place the two tarsi close together. These desired final values and the current values of the leg angles, α , β , and γ , are input to the swing net together with bias inputs and sensory inputs ($r1-r4$) that are activated by an obstruction blocking the swing and thereby initiate appropriate avoidance movements. NL is a nonlinear compensation term. The stance net uses the β joint for height control *via* a negative-feedback system. Walking velocity is controlled by a negative-feedback system, which compares v_{ref} and v_{sens} , and influences the α and γ gains. The α channels are further subject to a yaw control (angle θ), which stabilizes straight and curve walking. The sign of this influence is opposite for the left and right legs. Walking is switched on by another central influence, which passes through a maximum detector and influences the α channels of all legs.

stance to swing is crucial. A control system therefore also has to ensure proper spatiotemporal coordination among all legs.

Each single problem mentioned above can be solved by means of classical control algorithms; this is, however, very costly in terms of computational time. In contrast, insects, like all other animals equipped with a slow-processing neuronal system, solve all these problems in real time and, beyond this, are able to react immediately even to such extreme changes as, for example, the loss of a whole leg. The solutions invented by nature are therefore not only interesting for the biologist, but could also be useful for solving problems in robotics.

Control of the Gait

Results from biological investigations show that each leg is controlled by its own controller (*e.g.*, Cruse, 1990) and may indicate that even each leg controller consists of separate control networks (*e.g.*, Bässler, 1988). The relaxation oscillator making up the step pattern generator is assumed to consist of a swing net that controls the swing movement and a stance net that controls the movement of the leg during stance (Fig. 1b). The transition between swing and stance is controlled by the selector net. The swing net and the stance net are always active, but the selector net determines which of the two has access to the motor output at any given time. The decision of when to switch from one state into the other is completely determined by sensory input. The selector net consists of a two-layer feedforward net with positive feedback connections in the second layer. These positive-feedback connections serve to stabilize the ongoing activity, namely stance or swing. The three most important coordinating mechanisms used in our present model influence the selector net so as to modulate the beginning of a swing movement, and therefore the end-point of a stance movement (the posterior extreme position, PEP). These influences (numbers 1–3, summarized in Fig. 2) are described in detail elsewhere (*e.g.*, Cruse, 1990; Cruse *et al.*, 1998). The end of the swing movement in the animal is modulated by a single, caudally directed influence (number 4 in Fig. 2) that depends on the position of the next rostral leg. This mechanism is responsible for the targeting behavior—the placement of the tarsus at the end of a swing close to the tarsus of the adjacent rostral leg.

A computer simulation of this system showed proper temporal coordination of the legs when these are walking at different speeds on a horizontal plane (Cruse *et al.*, 1998). The steps of ipsilateral legs are organized in triplets forming “metachronal waves,” which proceed from back to front, whereas the steps of the contralateral legs on each segment step approximately in alternation. With increasing walking speed, the typical change in coordination from the tetrapod to a tripod-like gait is found. The coordination pattern is

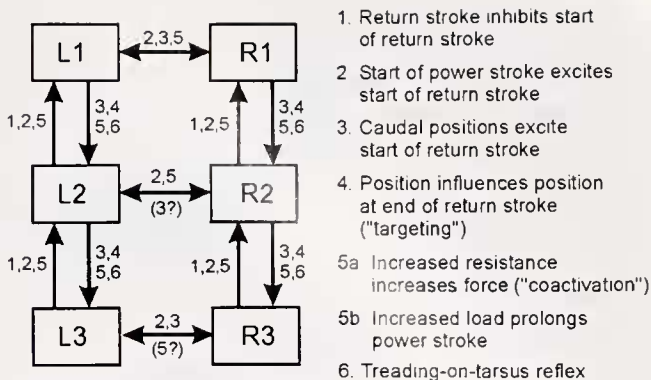


Figure 2. Summary of the main coordinating influences between adjacent legs during walking.

very stable. For example, when the movement of one leg is interrupted briefly during the stance, the normal coordination is regained immediately after the perturbation. Note that in our approach, the temporal sequence of the activities of the legs is not explicitly produced by a master timer but is implicitly determined by the connections between the leg controllers. These coordinating mechanisms had been successfully tested on a variety of six-legged robots (*e.g.*, Espenschied *et al.*, 1993; Ferrell, 1995; Pfeiffer *et al.*, 1995; Flannigan *et al.*, 1998; Frik *et al.*, 1999).

Control of the Swing Movement

The geometry of the stick insect's leg is shown in Figure 1a. The coxa-trochanter (β) and femur-tibia (γ) joints, the two distal joints, are simple hinge joints with one degree of freedom corresponding to elevation and to extension of the tarsus, respectively. The subcoxal (α) joint is more complex, but during forward walking most of its movement is in a rostrocaudal direction around the nearly vertical axis. The leg can thus be considered as a manipulator with three degrees of freedom for movement in three dimensions, and the control network must have at least three output channels, one for each leg joint. As has been shown by Cruse *et al.* (1998), a simple, two-layer feedforward net with three output units and six input units can produce movements that closely resemble the swing movements observed in walking stick insects. In the simulation, the three outputs of this net, interpreted as the angular velocities $d\alpha/dt$, $d\beta/dt$, and $d\gamma/dt$, are fed into an integrator (not shown in Fig. 1b), which in the animal corresponds to the leg itself, to obtain the joint angles. The actual angles are measured and fed back into the net. *Via* this loop through the environment, the network becomes a recurrent system. In addition to the actual angles of the three leg joints, three other input units (α_r , β_r , γ_r) represent the target of the swing movement, *i.e.*, the leg position that should be achieved at the end of the return stroke (targeting influence, number 4 in Fig. 2).

This system with only eight or nine nonzero weights is able to generalize over a considerable range of untrained situations. Furthermore, the swing net is remarkably tolerant with respect to external disturbances (Fig. 3). The learned trajectories represent a kind of attractor to which the disturbed trajectory returns. This compensation for disturbances is possible because the system does not compute explicit trajectories but—using actual sensor data—calculates only the next movement increment. This ability to compensate for external disturbances permits simple extensions of the swing net in order to simulate avoidance behaviors observed in insects (additional inputs “r1–r4” in Fig. 1b).

Control of the Stance Movement

To control the stance movement, it is not enough simply to specify a movement for each leg on its own: the mechanical coupling through the substrate means that efficient locomotion requires coordinated movement of all the joints of all the legs in contact with the substrate—that is, a total of 18 joints when all legs of an insect are on the ground. However, the number and combination of mechanically coupled joints varies from one moment to the next, depending on which legs are lifted. A further complication occurs when the animal negotiates a curve, because then the different legs move at different speeds.

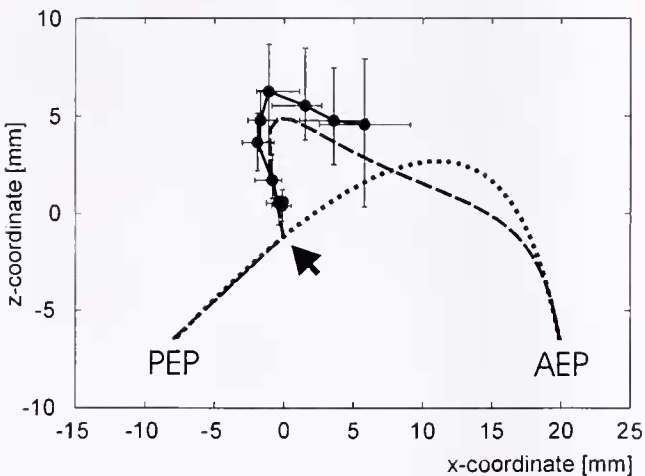


Figure 3. Behavior of the swing net. The fine stippled line represents a trajectory (in the x - z plane, *i.e.*, in a side view) of the tibia endpoint of a middle leg of an undisturbed swing movement. The leg lifts off at the posterior extreme position (PEP) and swings forward to the anterior extreme position (AEP). The dashed line represents a swing trajectory of the middle leg in which the movement of the tibia was obstructed (arrow). The swing net instantaneously generates a new trajectory, which avoids the obstruction by retracting and lifting the tibia and which then reaches the AEP on this new trajectory. The filled circles (with x - z error bars) connected by the continuous line show the reaction of a stick insect whose swing movement was obstructed at the same moment in swing as it was applied to the simulation.

In robots, these problems can be solved using traditional, though computationally costly, methods, because these approaches consider the ground-reaction forces of all legs in stance and seek to optimize some additional criteria, such as minimizing the tension or compression exerted by the legs on the substrate. Due to the nature of the mechanical interactions, and inherent in the search for a globally optimal control strategy, such algorithms require a single, central controller; they do not lend themselves to distributed processing. This makes real-time control difficult, even in the simple case of walking on a rigid substrate.

Despite the evident complexity of the task, it is mastered even by insects. Therefore, there must be a solution fast enough that on-line computation is possible even for slow-processing neuronal systems. How can this be done? To solve the particular problem at hand, we propose to replace a central controller by distributed control in the form of local positive feedback (Cruse *et al.*, 1995a). Positive feedback (or in other words, reflex reversals) had already been reported to occur during walking in the stick insect (*e.g.*, Bässler, 1988; Schmitz *et al.*, 1995). Compared to earlier versions of the leg controller (Cruse *et al.*, 1995b), this change permits the stance net to be radically simplified. The positive feedback occurs at the level of single joints: the position signal of each is fed back to control the motor output of the same joint (Fig. 1b, stance net). How does this system work? Let us assume that any one of the joints is moved actively. Then, because of the mechanical connections, all other joints begin to move passively, but in exactly the proper way. Thus, the movement direction and speed of each joint does not have to be computed, because this information is already provided by the physics. The positive feedback then transforms this passive movement into an active movement.

There are, however, several problems to be solved that are inherent in positive feedback systems. The first is that positive feedback using the raw position signal would lead to unpredictable changes in movement speed. This problem can be solved by introducing a kind of bandpass filter into the feedback loop. The effect is to make the feedback proportional to the angular velocity of joint movement, not the angular position. In the stick insect, the bandpass filter property can be attributed to the phasic response characteristic of the sense organs and the lowpass filter properties of the neuromuscular system. The second problem is that using positive feedback for all three leg joints leads to unpredictable changes in body height, even in a computer simulation neglecting gravity. A physical system would, of course, be pulled downward by gravity, and the positive feedback would accelerate this movement. In the stick insect, body height is controlled by a distributed system in which each leg acts like an independent, proportional controller (Cruse *et al.*, 1993). Thus, no master height controller is necessary; the only central information is the invariant reference value

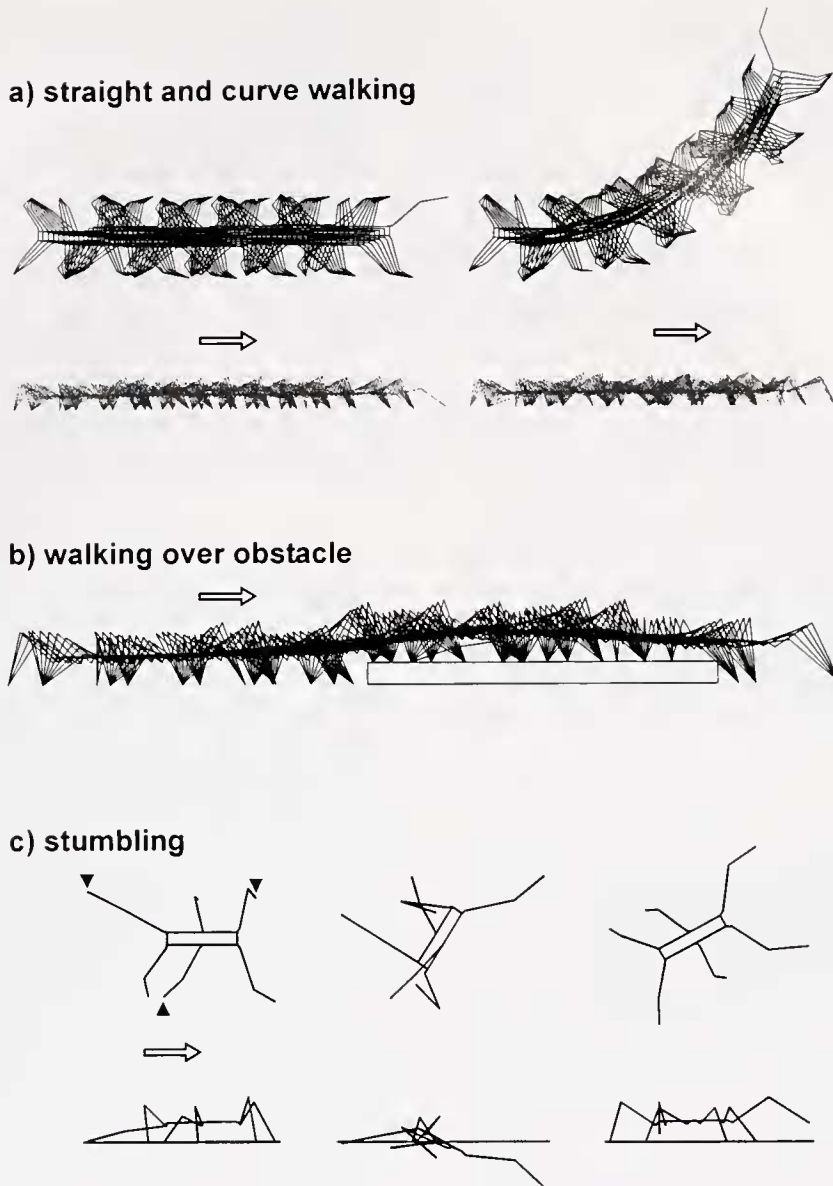


Figure 4. Strobe-shot video of a simulation of the six-legged system with negative feedback applied to all six β joints and positive feedback to all α and γ joints. Leg positions are shown only during stance and only for each fifth time interval. In (a), straight (angle $\theta_{ref} = 0$) and curve walking (angle $\theta_{ref} \neq 0$) is shown from both a top and a side view. Walking direction is from left to right. In (b), a straight walk over an obstacle (obstacle height is 90% of the normal body-substrate clearance) is shown from a side view. In (c), three single frames (both top and side view each) of a situation in which the system was forced to fall to the ground are shown. The fall caused an extremely disordered arrangement of the legs, but within a few seconds the system stood up by itself and resumed proper coordinated walking.

for each leg. In the WalkNet we implemented this such that only the α and the γ joints are under positive feedback control, whereas the β joint remains under classical negative feedback as in the standing animal. In this way, it is possible to solve the problems mentioned above in an easy and computationally simple manner. This hypothesis is also compatible with biological results obtained from animals

subject to disturbances during stance movements (Bartling and Schmitz, 2000).

Finally, we have to address the question of how walking speed is determined in such a positive feedback controller. We assume a central value that represents the desired walking speed v_{ref} . This is compared with the actual speed, which could be derived from the optical flow or by moni-

toring leg movement. An error signal, resulting from a deviation, modifies the gain of the positive feedback for all α and γ joints of all six legs accordingly (Fig. 1b, stance net). With our controller, curve walking is achieved in an easy way. Again we assume a central value that represents the intended angle of body yaw. A traditional negative feedback system controls the rate of yaw ($\dot{\theta}_{yaw}$, Fig. 1b). The error signal modifies the gain of the positive feedback of the legs. Keeping $\dot{\theta}_{ref}$ at zero results in straight walks: a bias to one or the other side results in curve walking with the curvature proportional to the amplitude of the bias (Fig. 4a).

Walking over irregularities in the terrain is performed sufficiently well due to the adaptive properties inherent in our control approach (Fig. 4b). Moreover, we found further emergent properties of the decentralized control structure. If the system was made to stumble and fall to the ground, it stood up by itself and resumed proper walking (Fig. 4c). This happened even when the fall placed the six legs in an extremely disordered arrangement. This means that the simple solution proposed here also eliminates the need for a special supervisory system to rearrange leg positions after such an emergency.

Summary

Considering the problems with which an adaptive control system for walking must cope, one could be inclined to propose a highly centralized system with global knowledge. Our biologically inspired model shows, however, that the most complex task (stance movement) can be handled by a rather simple system (local positive feedback). The simplification is possible because instead of explicit calculations, the physical properties of the system and its environment are exploited. This is shown in our model at several stages:

- The rhythmic movements of single legs are not produced by a top-down approach but emerge from the interaction of the neuromuscular system with the environment.
- For the swing movement, no explicit trajectory is pre-calculated and then spooled out; rather the trajectory is calculated on the basis of the actual sensor data of the ongoing swing.
- The discrepancy between the complexity of the task and the simplicity of the solution is most obvious for the control of the stance movement. Local rules for each single joint are sufficient to solve the given task in an adaptive way.

Furthermore, our simulation shows that at the systems level, complex behavior can emerge from the cooperation of local rules:

- The coordination mechanisms produce proper tripod or tetrapod gait. These gaits are robust against disturbances.
- The system, by combining local positive and negative feedback loops, can cope with a variety of disturbances such as restricting movement of a single leg or removal of leg segments.
- If the system was forced to stumble and fall to the ground, it stood up by itself and resumed proper walking.

These findings encourage us to propose a decentralized control scheme as a basis for legged robot locomotion. This basis can be extended to integrate further reflexes and behaviors, in order to achieve in the robot a level of agility similar to that found in insects.

Acknowledgments

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